

**Method for manufacturing sputter-coated substrates,
magnetron source and sputtering chamber with such source**

The present invention relates to plasma treating substrate surfaces, thereby especially to sputter-coating such
5 surfaces and even more specifically to directional sputtering realized as long-throw sputtering and/or ionized physical vapor deposition (IPVD). It possibly may also be applied for etching.

So-called collimated sputtering and long-throw sputtering
10 have been used for coating moderate aspect ratio holes. Ionized Physical Vapor Deposition, IPVD, has been used more recently to deposit films in holes. In the IPVD method a flux of ionized metal atoms is used. Such flux of positively charged metal ions is accelerated in the gap
15 between the plasma and the substrate, e.g. a silicon wafer which has a negative bias with respect to the plasma. As the electric field is perpendicular to the substrate as to a silicon wafer surface, this results in a superior bottom coverage of high aspect ratio holes. There are various ways
20 how to achieve high ionization fraction of metal for IPVD. One way is known from the US 6 352 629. Before discussing this prior art and proceeding to the present invention some definitions shall be established:

1. Magnetron magnetic field pattern

25 As exemplified in Fig. 1 a magnetron magnetic field pattern as established along a target surface 3 of a target 1 comprises, seen towards the target surface 3, a pattern of magnetic field F_M which forms a closed loop. In a cross-sectional view onto the target the magnetron magnetic field

pattern F_M is tunnel-shaped with magnetic field arcing from an outer area A_o of one magnetic polarity to an adjacent inner area A_i with the other magnetic polarity. The magnetic flux out of the outer area A_o which forms a substantially closed loop is substantially equal to the magnetic flux at the second, inner area A_i except the signum.

Thereby, we define the outer area A_o as confined by a closed loop locus line L' which is defined by the projection (dashed lines) of the locus L along the magnetic field pattern F_M along which the component of magnetic field perpendicular to the target surface 3 is zero.

Further, whenever the present invention is applied with etching the target surface 3 is of a non-sputtered material. For the preferred application of the present invention, i.e. for sputter-coating the target surface 3, the target surface is of a material to be sputtered and is therefore a sputtering surface.

2. Magnetron magnetic field with unbalanced component pattern

The magnetron magnetic field pattern becomes unbalanced if, departing from the balanced configuration as of (1), the magnetic flux along one of the inner A_i and of the outer - A_o - areas is increased relative to such flux at the other area. In fig. 1 there is schematically shown the generation of the magnetron magnetic field pattern F_M and, additionally, of an unbalanced field pattern F_U . Along the target 1 and adjacent the target surface opposite to the target surface 3 there is provided a magnet arrangement

with an inner magnet subarrangement 5 and a second outer magnet subarrangement 7. The surface of first subarrangement 5 facing the target 1 is of one magnet polarity, S, whereas the surface of the outer subarrangement 7 facing target 1 has the second magnet polarity, N. Between the two magnet subarrangements there is formed the magnetron field pattern F_M , whereby the magnetic flux at the surfaces of the two magnet subarrangements 7 and 5 is substantially equal.

- 10 Whereas in fig. 1 the field pattern F_M is generated by means of magnet subarrangements 5 and 7, which respectively have magnetic dipoles oriented perpendicularly to the target surface 3, this field pattern F_M may also be generated by respective magnet arrangements with magnetic
15 dipoles substantially parallel to the target surface 3, one pole providing for the magnetic flux at the inner area A_i , the other magnetic pole for the magnetic flux at the outer area A_o .

- The magnetron field pattern becomes unbalanced if according
20 to fig. 1 the magnetic flux at one of the respective surfaces with the subarrangements 5 and 7, according to fig. 1 at the outer area A_o , is significantly increased. There occurs, compared with the magnetron field pattern F_M , a considerable amount of magnetic flux F_u with long range.
25 In fig. 1 as an example there is shown a centered circular arrangement of the two subarrangements 5 and 7 with respect to a loop central axis A_L .

The unbalanced field pattern F_u is evenly distributed along the outer magnet subarrangement 7.

Such known unbalanced field pattern F_U is thus the result of increasing the magnetic flux e.g. at the outer area A_o with a homogeneous increase of magnetic flux density along a loop of that area A_o . In view of the present invention we
5 call such unbalanced field pattern F_U as of fig. 1 a symmetrically unbalanced field pattern.

Turning to the US 6 352 629 it may be seen that there is provided a magnet arrangement which generates a symmetrically unbalanced field pattern as was explained
10 with the help of fig. 1, which is moved around an axis offset from the loop central axis A_L of the symmetrically unbalanced circular magnetron. There is provided a DC coil which is wrapped around the space between the target and the substrate being sputter-coated so as to generate an
15 axial magnetic field guiding metal ions towards the substrate. The target area which is covered by the symmetrically unbalanced magnetron field pattern is considerably smaller than the overall sputtering surface. As a symmetrically unbalanced magnetron as shown in fig. 1
20 generates an extremely focused plasma on the loop central axis, the ion density at the substrate is strongly inhomogeneous.

It is an object of the present invention to provide a method for manufacturing substrates with a vacuum plasma
25 treated surface with an improved averaged homogeneity of plasma density distribution over the substrate surface and accordingly to propose a respective magnetron source and treatment chamber. Applied for IPVD, the present invention, due to the addressed homogeneity of plasma exposure along

the substrate surface, leads to an improved homogeneity of averaged metal ion exposure of the substrate surface.

The addressed object is reached by the method of manufacturing substrates with a plasma treated surface

5 which comprises the steps of

- providing a target with a target surface;
- providing at least one substrate, i.e. one single substrate or more than one substrate, distant from and opposite the target surface.

10 Along the target surface there is generated a magnetic field pattern of a magnetron field - as of F_M of fig. 1 - forming a closed loop considered in direction towards the sputtering surface and, considered parallel to the sputtering surface, tunnel-like arcing from an outer area -
15 A_0 - of first magnetic pole to an inner area - A_i - of second magnetic pole, whereby the inner area - A_i - is confined with respect to the outer area - A_0 - by a closed locus - L' - of zero component of magnetic field perpendicular to the target surface of the magnetron field
20 pattern - F_M .

The magnet field pattern further comprises an unbalanced long-range field pattern which is asymmetrical and is generated by increasing magnetic flux along the outer area relative to magnetic flux along the inner area, whereby the
25 long range field reaches the substrate surface with a component of magnetic field parallel to the substrate surface of at least 0.1 Gauss. In the magnetic field pattern there is generated a plasma discharge and the

substrate surface is plasma treated, whereby the asymmetrically unbalanced field pattern is swept along the substrate surface.

Thus, not a symmetrically unbalanced magnetron, but an
5 asymmetrically unbalanced magnetron is exploited.

3. Asymmetrically unbalanced magnetron field pattern

So as to fully understand the present invention as is going to be described with preferred embodiments the principal of an asymmetrically unbalanced magnetron as inventively
10 exploited by the present invention shall be exemplified with the help of fig. 2.

According to fig. 2 there is generated in analogy to the embodiment of fig. 1 the magnetron magnetic field pattern F_M . As further shown in fig. 2 the magnetic flux along the
15 surface of the second, outer magnet subarrangement 7_a is increased. If this was done homogeneously distributed along the outer magnet subarrangement 7 this would lead to a symmetrically unbalanced field pattern component F_U according to fig. 1 and as introduced in fig. 2 in dashed
20 lines.

Nevertheless, and according to the present invention as shown in fig. 2 the inventively exploited asymmetrically unbalanced field pattern F_{AU} is most generically realized by disturbing the symmetrically unbalanced field pattern F_U
25 so that the respective field pattern is distorted in a direction parallel to the target surface 3 (see fig. 1). This is performed in a preferred embodiment by inhomogeneously increasing the magnetic flux density along the outer area A_o . As exemplified in fig. 2 such

inhomogeneous increasing of magnetic flux density in an azimuthal direction along the outer area A_0 is realized in one preferred embodiment in that there is locally applied a further magnetic field along a loop in the outer area as by providing along the outer area A_0 additionally to the first part 7a of magnet subarrangement 7 - which provides for symmetrically unbalanced pattern F_U - a second magnet subarrangement part 7b, which is only provided along the predetermined area of outer area A_0 and thus locally applies the further magnetic field. Thereby this further field distorts the symmetrical unbalanced field pattern F_U resulting in the asymmetrically unbalanced field pattern F_{AU} .

Turning back to preferred embodiments of the present invention, in a first preferred embodiment the target surface is a sputtering surface and plasma treating of the substrate surface is sputter-coating. Nevertheless, the method according to the present invention may also be applied for etching, e.g. for reactive plasma-enhanced etching of the surface of the substrate. In this case the target surface is selected of a material not being sputtered and the magnetron source with the inventively exploited asymmetrically unbalanced field pattern being swept along the surface of the substrate is merely provided for generating the respective plasma distribution. No material is freed from the target surface.

In a further preferred embodiment of the method according to the present invention the component of magnetic field

parallel to the substrate surface is selected to be between 1 Gauss and 20 Gauss.

Further preferred, the tunnel-like magnetron field pattern - F_M - covers more than 60 % of the target surface, thereby
5 even more preferred, more than 85 % of the target surface. Thereby, especially with an eye on performing sputter coating of the substrate surface, it is advantageous to apply the addressed covering because it is primarily in the area covered by the magnetron field pattern - F_M - in
10 which, due to electron-trap effect, an increased plasma density is reached and material is sputtered off at high rate.

As was addressed above the asymmetrically unbalanced field pattern is realized in one preferred embodiment by
15 disturbing homogeneity of an increased magnetic flux density along the outer area - A_o - by locally applying a further magnetic field along said outer area. Thereby, said further magnetic field is preferably generated by at least one permanent magnet and/or at least one electromagnet.
20 Providing an electromagnet allows control of such further magnetic field so that also during processing the asymmetry of the unbalanced field pattern may controllably be varied.

In a further preferred embodiment not only the asymmetrically unbalanced field pattern is swept along the
25 substrate surface, but the magnetron field pattern too. Due to the fact that the magnetron field pattern is also moved with respect to the substrate further increased treatment homogeneity is reached, especially with an eye on sputter coating.

In a further still preferred embodiment sweeping of the asymmetrically unbalanced magnetic field pattern along the substrate surface is performed by circularly moving the unbalanced magnetic field pattern around an axis which is perpendicular to the target surface.

With an eye on fig. 2 it may be seen that the asymmetrically unbalanced field pattern F_{AU} is moved along a circular path around an axis A_S , whereby the location of such axis A_S is selected remote from the area P of maximum flux of the asymmetrically unbalanced field pattern F_{AU} .

As further also shown in fig. 2 in a preferred embodiment sweeping is generated by moving the magnetron - F_M - as well as the asymmetrically unbalanced field pattern F_{AU} around an axis which is perpendicular to the target surface and which is offset from a geometrical center - A_L - of the inner area A_1 , so that by such moving both field patterns are swept with respect to the substrate surface.

In a further preferred mode the loop of magnetron field pattern is generated circularly around a loop central axis, as shown in fig. 2 around axis A_L .

In a further preferred embodiment of the method according to the present invention there is generated by the asymmetrically unbalanced field pattern - F_{AU} - an area of maximum plasma density as shown at P of fig. 2 adjacent the periphery of the substrate surface and said maximum area is swept adjacent to and along this periphery.

In fig. 2 the substrate 6 is shown in dashed line representation. It is centered about axis A_S . The area P of

maximum plasma density sweeps along the periphery of substrate 6 and adjacent to such periphery.

Further, in a preferred embodiment controlled adjusting of uniformity of ion current density at the substrate surface
5 is performed by adjusting the further magnetic field which, as was explained, is provided for disturbing homogeneity of the unbalanced field pattern to make it asymmetrically unbalanced.

As was already addressed and with an eye on controllability
10 of the asymmetrically unbalanced field pattern - F_{AU} - providing an electromagnet for generating such further magnetic field is most advantageous. Thereby, in a further preferred embodiment there is provided at least one coil which generates a magnetic field which is substantially
15 parallel to the target surface. With an eye on fig. 2 such magnetic field is schematically shown at F_a . Thereby, it may be seen that by varying such field F_a generated by the said at least one coil the pattern of the asymmetrically unbalanced field F_{AU} may be controllably adjusted. This
20 leads to the further preferred mode that generating sweeping of the asymmetrically unbalanced pattern along the substrate surface comprises supplying the at least one coil with an alternating current which will generate an alternating field F_a , thereby sweeping the pattern F_{AU} and
25 thus the area P in an oscillating manner in the direction of F_a . If, in a further preferred embodiment, more than one of these coils are provided which generate respectively magnetic fields in different directions as e.g. and with an eye on fig. 2 additionally in direction of F_b ,

perpendicularly to the direction of F_a , and alternative currents are applied to the respective coils, the asymmetrically unbalanced field pattern F_{AU} and thus area P will be swept in two dimensions along the surface of the substrate 6 and by appropriately selecting amplitudes, mutual phasing and/or frequencies of the alternating currents applied to the coil the sweeping pattern may be selected and controllably adjusted in the sense of realizing for sweeping of area P Lissajoux patterns along the substrate surface.

In a further preferred embodiment the substrate is selected to be circular and the asymmetrically unbalanced field pattern is swept around a center axis of the substrate, whereby if more than one substrate is provided the substrates are arranged within a circular area and the center axis is defined with respect to such circular area.

In a further preferred embodiment the current of ions at the substrate surface is adjusted by adjusting magnetic field components perpendicular to the substrate surface. Such component is on one hand adjustable by adjusting the asymmetrically unbalanced field pattern F_{AU} , but may additionally or alternatively be performed by applying, e.g. by means of a Helmholtz coil arrangement, a controllably variable additional magnetic field perpendicularly to the substrate surface, namely a magnetic field F_c as shown in fig. 2. In a further preferred embodiment the electron current in the plasma is guided substantially perpendicular to the target surface towards the substrate surface which may be realized by applying a

respective electrical potential difference between target surface and substrate surface and/or by providing appropriate shielding.

In a further preferred mode the plasma as generated is
5 electrically fed by a pulsating supply voltage. Thereby, further preferred, the frequency f of pulsating is selected to be

$$5 \text{ kHz} \leq f \leq 500 \text{ kHz}$$

thereby to be preferably

10 $100 \text{ kHz} \leq f \leq 200 \text{ kHz}.$

In a further preferred embodiment the duty cycle of such pulsating is selected to have 1 % to 99 % off-times (both values included), thereby to have, even more preferred, off-times of between 35 % and 50 % (both limits included).

15 Especially for long-throw and/or IPVD applications there is established a total pressure in the vacuum chamber to be at most 10^{-1} Pa, thereby preferably

$$10^{-2} \text{ Pa} \leq p \leq 5 \times 10^{-2} \text{ Pa}.$$

Further, in a preferred mode the substrate is biased with
20 an Rf frequency power, whereby adjusting of the energy of ions bombarding the substrate surface comprises adjusting such Rf power. In a specially preferred embodiment for sputter-coating the substrate surface the target surface is provided with a sputtering surface of one of Ti, Ta, Cu.

25 With an eye on figs. 1 and 2 it must be emphasized that the magnet arrangement which generates the magnetron field pattern F_M is not necessarily selected circularly as shown

in these figures, but such magnetron field pattern and respectively the magnet arrangements generating such pattern may be conceived to achieve a desired target erosion profile in sputter coating and a required thickness
5 uniformity of coating on the substrate surface.

Appropriately tailoring the magnetron field pattern F_M and especially its looping shape in a view towards the target surface is known in a huge variety to achieve the addressed desired results.

10 Following up the above mentioned object there is further proposed a magnetron source which comprises

- a target with a target surface and an opposite surface;
- a magnet arrangement adjacent the opposite side and
15 having
 - at least one first magnet subarrangement;
 - at least one second magnet subarrangement;
 - said first magnet subarrangement having a first area pointing towards the opposite surface of said
20 target and being of one magnetic polarity;
 - the second magnet subarrangement having a second area pointing towards the opposite surface of said target and having the other magnetic polarity;
 - the second area forming a loop around and distant
25 from the first area;
 - the first area generating a first magnetic flux through the target surface;

- the second area generating a second magnetic flux through the target surface and wherein
- the second magnetic flux is larger than the first magnetic flux and is unevenly distributed along the second area.

5

- a sweeping arrangement which moves the unevenly distributed magnetic flux along the target surface.

According to the present invention there is further proposed a magnetron treatment chamber which comprises a magnetron source according to the present invention and as
10 was generically discussed above as well as a substrate carrier which is remote from and opposite to the target surface of the magnetron source.

Additionally to the figures addressed and the disclosure
15 given above the present invention shall become even clearer to the skilled artisan by the further description of preferred embodiments by means of figures as well as by the appending claims. The further figures show: /

Fig. 3 most schematically and simplified a magnetron
20 treatment chamber according to the present invention incorporating a magnetron source according to the present invention and operated for manufacturing substrates according to the present invention;

25 Fig. 4 in a representation in analogy to those of the figs. 1 and 2, the realization of a symmetrically unbalanced field pattern which is swept along a

substrate surface by being moved around an axis perpendicular to the target surface;

Fig. 5 over the radius of a circular substrate the ion
current density as resulting from operating the
5 chamber as of fig. 3 configured with the source as
of fig. 4 and with varying coil current - J -
parameter;

Fig. 6 in a representation in analogy to that of fig. 5
the ion current density as results when the
10 chamber as of fig. 3 is operated according to the
present invention with an asymmetrically
unbalanced field pattern as of fig. 2, again with
different coil currents - J - as parameter;

Fig. 7 in a most schematic representation a further
15 embodiment for realizing an asymmetrically
unbalanced magnetic field pattern swept along the
substrate surface;

Fig. 8 in a representation in analogy to that of fig. 7
still a further embodiment for realizing the
20 asymmetrically unbalanced field pattern and
sweeping with such field pattern along the surface
of the substrate;

Fig. 9 in a simplified and schematic representation in
analogy to that of the Figs. 1, 2 and 4 a further
25 embodiment of target and magnet arrangement to
generate an asymmetrically unbalanced field
pattern according to the present invention;

Fig. 10 as a function of pulsating frequency the ratio of metal ions Ti^+ to argon ions Ar^+ resulting at the substrate surface when treated according to the present invention, thereby supplying the magnetron source with a pulsating voltage of the addressed frequency;

Fig. 11 the ratio as of fig. 9 as a function of off-time % of said pulsating supply voltage with respect to pulse repetition period;

Fig. 12 again the addressed ratio as a function of working gas pressure, namely argon pressure, and

Fig. 13 again the addressed metal ions to working gas ions ratio as a function of electrical power supplied to the magnetron source.

In fig. 3 there is schematically and simplified shown a treatment chamber according to the present invention, especially a sputter-coating chamber, incorporating a magnetron source according to the present invention and performing the method of manufacturing according to the present invention. The treatment chamber according to fig. 3 is the today's preferred embodiment which is trimmed for long-throw and/or IPVD sputter coating of substrates and combines preferred features, some of which may be deleted for specific applications.

The chamber comprises a circular target 10 and a magnet arrangement 12 driven around rotational axis A_s by means of a motor drive as schematically shown at 14. Opposite the sputtering surface 13 of the target 10 and centered on axis A_s there is provided a substrate carrier 16 for centrally

positioning a substrate arrangement 18 of one or more than one substrate to be sputter-coated. At least one coil 20 is mounted outside and along the walls 22 of the sputtering chamber with a coil axis coincident with axis A_s .

5 Additionally or alternatively permanent magnets can be used to generate a magnetic field coaxially to axis A_s . An anode arrangement 24 is provided adjacent to the substrate carrier 16 and is substantially hidden from the processing space PR by means of a first shield 26 and a second shield
10 28 which shields substantially confine the processing space with respect to anode arrangement 24 and inner surface of chamber wall 22. The substrate carrier 16 is either operated electrically floating or on a DC bias potential or on an AC or AC plus DC potential, up to and preferably to
15 frequencies in Rf range.

By means of the first and second shieldings 26 and 28 electrons within the plasma processing space PR are substantially hindered from flowing onto the chamber wall 22. The shields 26 and 28 may equally or differently be
20 operated at electrically floating potential or on a DC potential, thereby preferably on an anodic electric potential. At least shield 28 is preferably electrically operated on an electric potential which is more negative than the electric potential applied to anode arrangement
25 24.

Thereby, only one, two or more shields may be provided electrically driven differently or equally. By such shields electrons in the plasma and in the processing space PR are guided to flow substantially parallel to the axis A_s

towards the substrate arrangement 18 on the substrate carrier 16. For certain applications it is also possible not to use any lateral shielding.

By means of the at least one coil 20 there is generated an additional magnetic field, F_c in Fig. 2, in the processing space PR substantially parallel to the axis A_s . It is also possible not to make use of any such coil arrangement 20 or to provide more than one such coil arrangement. They are (not shown) operated with DC power. The orientation of the magnetic field generated by the coils 20 may be oriented in one and the same direction, or at least one coil can generate a magnetic field in opposite direction to produce mirror-like magnetic fields.

For experiments the chamber as schematically shown in fig. 3 was conceived as follows:

Target material:	Ti
Target diameter:	300 mm
Shape of processing chamber and shieldings:	cylindrical
Distance from substrate carrier to sputtering surface:	
20	330 mm/370 mm
Diameter of circular single substrate carrier:	
	200 or 150 mm
Supply of plasma discharge:	DC or pulsed power
Single coil current:	10 A
25 Axial magnetic field by single coil:	
	10 Gauss

Bias of the substrate carrier: DC power

Target-to-substrate distance: 37 cm

As a first reference experiment the magnet system 12 was conceived according to fig. 1. Thus, there was applied an unbalanced magnetron with cylindrically symmetrical design. The long range of the symmetrically unbalanced magnet field pattern F_U according to fig. 1 was varied by varying the DC current supply of the coil arrangement 20 according to fig. 3 with current polarity strengthening the unbalancing magnetic field pattern F_U according to fig. 1. The large area symmetrical unbalanced magnetron arrangement was operated at a very low working gas pressure as of Ar, down to 0.025 Pa.

With an eye on fig. 1 it becomes clear that rotating this magnet arrangement around the loop central axis A_L , which is coincident with axis A_S as of fig. 3, has no effect.

As a function of the coil current in coil arrangement 20 there is generated a sharply focused plasma beam concentrated in the centre of the substrate.

As a next reference experiment the magnet system 12 was changed from the system according to fig. 1 to the system according to fig. 4, still a prior art magnet system, e.g. according to the US 6 352 629. The magnet system as shown in fig. 4 is different with respect to that shown in fig. 1 by the fact that the loop central axis A_L is offset from the rotating axis A_S . In the specific experiment considered the loop central axis A_L was offset from the axis A_S by a relatively small amount of 15 mm. This to keep the advantage of a large plasma confinement by the large

symmetrically unbalanced magnetron covering nearly the full sputtering surface of the target (fig. 4). The ion density along the substrate surface to be sputter-coated was measured. The result is shown in fig. 5.

5 In spite of the fact that the symmetrically unbalancing field pattern F_0 is swept along the surface of the substrate arrangement with a maximum density area P according to fig. 4 offset from the rotational axis A_s , there resulted a centrally focused plasma distribution up
10 to a sharply focused plasma beam in dependency of the coil current applied. The coil current by which the characteristics of fig. 5 are parameterized varies between 0 and 30 A. Further, there were applied five coil arrangements 20 as of fig. 3 operated at equal DC currents.

15 The substrate holder 16 of fig. 3 was operated at a bias of -80 V DC, an Ar flow was established of 15 sccm and a total pressure p of 0.14 Pa. The distance established between the sputtering surface and the substrate was 370 mm to experience long-throw effect.

20 As a third experiment now according to the present invention the magnet arrangement was changed to that as shown and as was described with the help of figure 2. The respective result is shown in fig. 6 in analogy to the results of fig. 5. It may clearly be seen that again
25 dependent on the coil current the current density may be increased to values up to those experienced according to figure 5, but with a significantly improved uniformity of plasma density distribution and thus ion density distribution along the substrate arrangement surface, up to

a radius of 100 mm. This is especially true for a medium-range coil current of 4 to 10 A.

With an eye back on the magnet arrangement of fig. 2 and as was already addressed in the introductory part, fig. 7

5 shows in a representation in analogy to that of fig. 2 an alternative technique of sweeping the maximum plasma density area P along the surface of the substrate arrangement. Thereby, the first and second magnet subarrangements 5 and 7 are kept stationary, looping around
10 the loop centre axis A_L which is coincident with the rotational axis A_S which is further the central axis of the substrate arrangement. Thereby there is first generated a symmetrical unbalanced magnetron field according to fig. 1. The part 7_b of the second magnet arrangement 7, which is
15 responsible for achieving asymmetrical unbalancing as was explained with the help of fig. 2, is drivingly rotated around the central axis $A_L = A_S$, thereby sweeping cyclically the maximum plasma density area P as of fig. 2 along and adjacent (not shown) the substrate surface.

20 Fig. 8 shows in a representation in analogy to that of fig. 7 a further preferred embodiment for generating the asymmetrically unbalanced magnetic field pattern F_{AU} as of fig. 2 and sweeping this pattern along the substrate surface. Again the magnetron field pattern F_M is generated
25 between part 7a of magnet subarrangement 7 along the outer area A_o and the magnet subarrangement 5 at the inner area A_i . The part 7a of the outer magnet subarrangement 7 provides for the symmetrically unbalanced field pattern F_u according to fig. 2. Asymmetry is realized by providing a

first coil arrangement 80_a adjacent and below the target surface at the magnet subarrangement 7 which coil arrangement 80_a generates a magnetic field F_a , as shown also in Fig. 2, parallel to and in radial direction along the target surface. As now evident to the skilled artisan by applying this magnetic field F_a the formerly symmetrically unbalanced magnetic field pattern F_U becomes an asymmetrically unbalanced field pattern F_{AU} . By applying to the coil arrangement 80_a, which is in fact an electromagnet arrangement, an alternating current I_a the area P of maximum field flux as of Fig. 2 is swept along the substrate surface forth and back as a function of amplitude of the applied current, shape of the current course over time, and frequency.

Whenever, in a further preferred embodiment, there is applied at least one second coil arrangement 80_b the same prevails as was explained with respect to the effect of coil arrangement 80_a, but because the second coil arrangement 80_b generates a magnetic field F_b as also shown in Fig. 2 e.g. perpendicularly to the direction of field F_a , the area P of maximum flux is moved along the substrate surface as a result of the superposition of the two magnetic field components F_a and F_b . As known by the skilled artisan the trajectory path of area P along the substrate surface may controllably be adjusted by selecting mutual phasing of the two currents I_a , I_b feeding the two coil arrangements, their amplitudes, their frequencies as well as the shape of their time courses. Controlling the trajectory path of area P is thus realized following principally the well-known rules of Lissajoux.

Fig. 9 shows a further embodiment of a magnet assembly at the target resulting in an asymmetrically unbalanced magnet field pattern. This assembly has a first looping magnet subarrangement 87_o of one polarity and having a radius-like extension 87_{o1} . The second magnet subarrangement 87_i is provided distant from and along the outer magnet subarrangement 87_o . These two magnet subarrangements do generate on one hand the magnetron field pattern F_M and the asymmetrically unbalanced field pattern with an area P of maximum flux as shown in fig. 9. The locus of zero field component of the magnetron field pattern F_M defines for the locus L' as was already shown in Figs. 1 and 2, thereby confining the outer area A_o with respect to the inner area A_i . Thereby, at the right-hand side of the arrangement of Fig. 9 the outer magnet subarrangement 87_o projects from the respective edge of the target arrangement shown at 88. The projecting area A_Δ of magnet subarrangement 87_o causes the asymmetry of the unbalanced magnetic field. Only at that area A_Δ the magnetron field pattern F_M does not emanate from the target surface which is limited at line 88. This area A_Δ is not more than 12 % of the target surface area.

When performing the method according to the present invention, i.e. operating the magnetron source and magnetron chamber, especially for sputter-coating the following further settings are preferred:

The plasma is preferably fed with a power in the range of 0.1 to 60 kW, thereby even more preferred within a range of 1 to 40 kW.

The target surface is preferably exposed to a plasma density of 0.1 to 900 W/cm², thereby even more preferred to a plasma density of between 10 and 50 W/cm².

5 As was already addressed and in spite of the fact that the substrate may also be biased with DC, such biasing is preferably realized with Rf power. Such biasing Rf power has preferably a power density of 0.01 to 10 W/cm², even more preferred of 0.2 to 2 W/cm² per cm² of substrate surface.

10 Ion bombarding of the substrate is preferably adjusted to energy values of between 0.1 eV and 300 eV, which preferably comprises appropriately adjusting the Rf power which biases the substrate.

15 Further, especially when performing long-throw sputter-coating, the energy of ions bombarding the substrate surface is adjusted to values between 0.01 eV and 50 eV and the ion density of these ions is adjusted to less than 0.2 mA/cm² preferably by adjusting the gas pressure within the range of 10^{-2} Pa $\leq p \leq 5 \times 10^{-2}$ Pa and the magnetic flux
20 perpendicular to the substrate surface to a value which is less than 0.5 Gauss.

For IPVD application the energy of ions bombarding the substrate is adjusted preferably to values between 20 eV and 300 eV and the ion density of these ions is selected in
25 the range of 0.2 to 10 mA/cm² by setting working gas pressure in the vacuum chamber between 3×10^{-2} Pa and 5×10^{-1} Pa, selecting the magnetic field perpendicularly to the substrate surface to be between 0.5 Gauss and 50 Gauss.

The radial uniformity of ion current density at the substrate surface is further preferably adjusted by adjusting the magnetic flux of the magnetic field component perpendicularly to the substrate surface. Especially when
5 long-throw sputtering one of the metals Ti, Ta or Cu the metal ionization degree adjacent the substrate surface is adjusted preferably to a level of less than 10 % which is done by adjusting at least one of pressure, electric power to the magnetron source, pulsing characteristic of the
10 electrical magnetron supply and magnetic flux of field components perpendicular to the substrate surface.

On the other hand e.g. when sputtering Ti, Ta or Cu the metal ionization may be selected at a level which is more than 20 %, even more than 50 %, by adjusting at least one
15 of pressure in the magnetron chamber, electric power applied to the magnetron source, pulsating characteristic of supply power to the magnetron source and magnetic flux of magnetic field perpendicularly to the substrate surface.

Further, whenever holes in a substrate have to be coated by
20 the method according to the present invention this is preferably performed in at least two subsequent steps. The first step consists of a long-throw sputtering step with metal ionization degree especially of one of the metals Ti, Ta, Cu of more than 20 %, preferably even of more than 50
25 %, which is adjusted as was just outlined above. In a second subsequent step, which is an IPVD step, the metal ionization degree of the addressed metal is adjusted by the parameters as outlined above to a level which is less than 10 %.

In a further preferred embodiment of the present invention the plasma is generated only for ignition with the help of a working gas as e.g. argon and then only metal atoms are present in the reaction volume of the chamber.

5 Further, and with an eye on the magnetron chamber as shown in Fig. 3 the asymmetrically unbalanced magnetic field pattern which is swept along the substrate surface may be passed during predetermined amounts of time or during
predetermined extents of sweeping trajectory path, beneath
10 a magnetic shield provided between the magnetron source and substrate surface so as to shield at least a part of the asymmetrically unbalanced magnetic field pattern from reaching and affecting treatment at the substrate surface.

Experiments have been performed to determine the metal
15 ionization ratio and its dependencies at the substrate surface which led to the above preferred embodiments. An energy-resolved mass spectrometer was used to measure the ratio between the intensity of Ti ions $^{48}\text{Ti}^+$ and argon ions $^{36}\text{Ar}^+$. The ratio of their intensities reflects the metal
20 ionization probability. The results are shown in the figures 10 to 13. One can see that the rate of metal ionization can vary in a very broad range. Higher working gas pressure as well as higher sputtering power according to the results of figs. 12 and 13 lead to an increase of Ti
25 ionization relative to Ar ionization, even when DC sputtering.

Moreover with predetermined fix electrical supply power to the magnetron source and predetermined fix pressure in the magnetron chamber pulsating of the magnetron supply and

thus of the magnetron discharge helps to ionize the metal with increased degree. From Fig. 11 where the metal ionization ratio is shown in dependency of the percentage amount of off-time at the pulsating electric magnetron source supply it becomes evident that with increasing off-time percentage the metal ionization increases. At a duty cycle with 50 % off-times of the pulsating electrical magnetron source supply Fig. 10 reveals a preferred optimum frequency range between 100 and 200 kHz for optimum metal ionization.

Especially in long-throw sputtering mode the coating of the bottom and sidewalls of high-aspect ratio holes in the substrate surface can be realized with neutral metal atoms sputtered at very low working gas flows and thus low pressures between 5×10^{-3} Pa and 5×10^{-2} Pa to avoid collision between metal atoms and gas atoms. The described large coverage of the whole target surface with plasma also during ON-time spans of the pulsating supply of the magnetron source allows working at extremely low-pressure neutral metal atoms eliminating damage of the holes in the substrate surface by excessive ion bombardment.

The arrangement also allows an IPVD step using higher pressures for higher bottom and sidewall coverage exploiting all the effects of high ionization including the resputtering by argon and metal ions.

Especially for IPVD applications, where the bottom of holes with high aspect ratio is coated by metal ions and resputtering from the bottom layer coats the sidewalls, a high flow and thus high pressure between 5×10^{-2} Pa and 2

Pa is used to create predominantly metal ion deposition. Measurements have shown that the processing according to the present invention is able to produce more than 50 % ionization in the case of Ti sputtering when all the plasma
5 confinement and ionization facilities are used: The asymmetrically unbalanced field pattern, the confining field of the coils 20 as of Fig. 3, floating shielding 28 and 26 of Fig. 3, an anode 24 close to the substrate, selecting proper pressure range and pulsating the
10 electrical magnetron source supply as described above. It should be stressed that the same configuration allows a uniform ion current density over the substrate in the range below 5 % resulting in very uniform conditions for step coverage at the substrate.

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